Stability Concerns for Large Blades

Wind Turbine Blade Workshop

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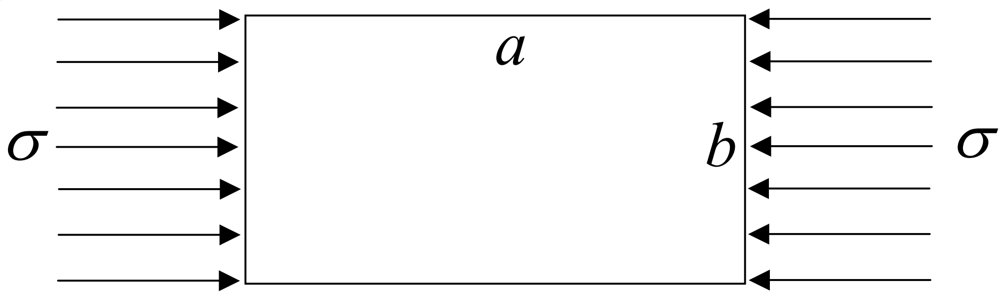
Stability Issues

- **Static panel buckling:**
  - * Effect of scale
  - * Addition of carbon
- **Dynamic resonance:**
  - * Effect of scale
  - * Effect of softening
  - * Addition of carbon
- **Stall flutter:**
  - * Effect of scale
  - * Design for avoidance
- **Classical flutter:**
  - * Effect of scale
  - * Effect of design evolution
  - * Design for avoidance
  - * Accuracy of quasi-steady aerodynamics

Static Panel Buckling Issues



$$t/b < 0.1$$

$$\sigma_{cr} = K \frac{E}{1-\nu^2}\left(\frac{t}{b}\right)^2$$

- σ_{cr} independent of scale
- Introducing carbon fibers, $E' > E, \quad t' < t$ such that $E't' = Et$

  can reduce buckling margins: $\dfrac{\sigma'_{cr}}{\sigma_{cr}} = \dfrac{t'}{t} < 1$

Dynamic Resonance Issues

$$\omega_{flap} = \frac{3.515}{l^2}\sqrt{\frac{EI}{\rho A}} \quad , \quad \omega_{twst} = \frac{\pi}{2l}\sqrt{\frac{G}{\rho}} \quad , \quad \Omega = \frac{U \times TSR}{l}$$

- ω_{flap}, ω_{twst}, and Ω all scale with $1/L$ (L is the scale). Thus per rev natural frequencies do not change with scale.
- Softening the blade by increasing l to l' modifies per rev frequencies: $$\frac{\omega'_{flap}}{\Omega'} = \frac{l}{l'}\frac{\omega_{flap}}{\Omega} \quad , \quad \frac{\omega'_{twst}}{\Omega'} = \frac{\omega_{twst}}{\Omega}$$
- Introducing carbon fibers maintains stiffness while reducing weight, generally increasing per rev frequencies.

Stall Flutter Issues

- **Usually occurs when a significant portion of the blade is experiencing aerodynamic stall.**
- **Probably independent of scale.**
- **Design for preclusion of stall flutter**
  - *** Make design choices that minimize the occurrence of stall – pitch control, airfoil section, etc.**
  - *** Minimize distance between center of pressure and elastic axis**
  - *** Minimize thickness ratio, aspect ratio and camber**
  - *** Add edgewise and torsional damping**

Classical Flutter Instability

- **Issues:**
  - * **Effect of scale and of evolution of design practices (larger modern designs versus older, simpler, much smaller designs)**
  - * **Accuracy of approximate quasi-steady aerodynamic theory (versus unsteady theory) in predicting classical flutter**
- **Characteristics:**
  - * **Aerodynamic theories originally developed for fixed wing aircraft (Theodorsen)**
  - * **Theories based on linear unsteady aerodynamics**
  - * **Flutter mode characterized by simultaneous bending and pitching motion**
  - * **Damping in flutter mode rises dramatically with airspeed before plunging to negative values at the flutter speed**

Classical Flutter Issue: 2D Scaling

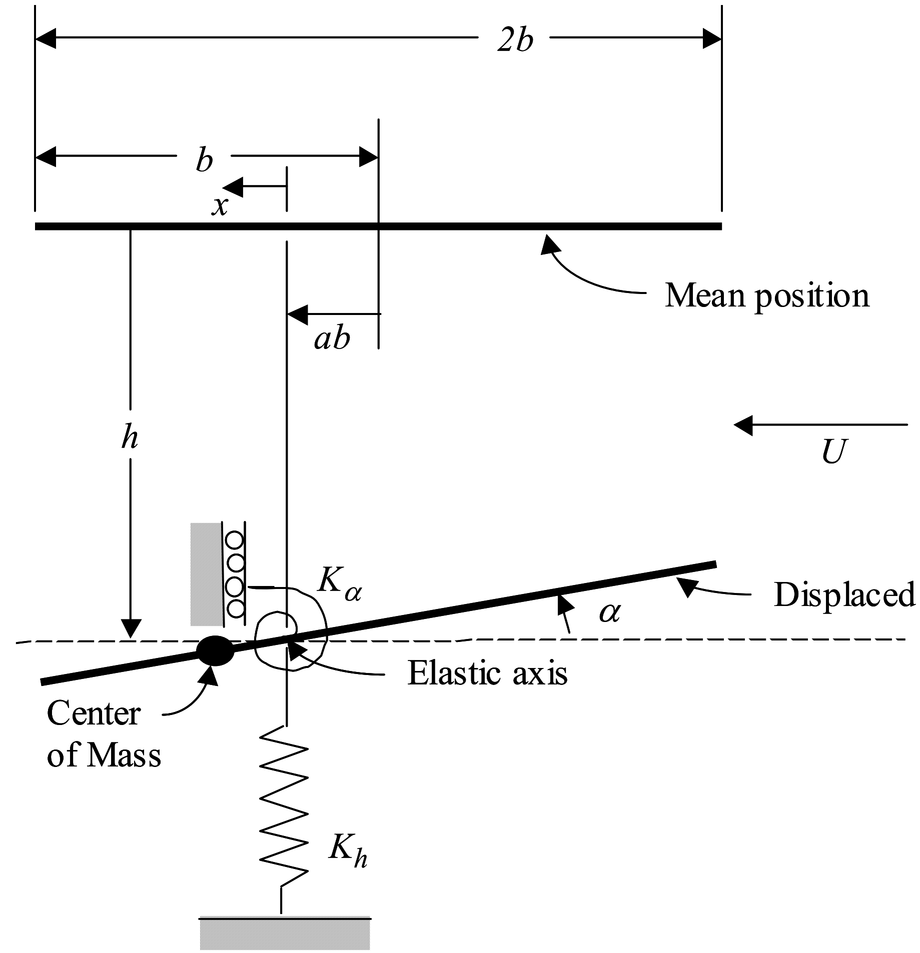
$$r_\alpha^2 = \frac{\int \rho x^2 dx}{b^2 \int \rho dx} = \frac{I_\alpha}{b^2 m}$$

$$x_\alpha = \frac{\int \rho x dx}{b \int \rho dx} = \frac{x_{cg}}{b}$$

$$\omega_h / \omega_\alpha , \; a , \; m / \pi \rho_\infty b^2$$

- With the above dimensionless quantities held fixed, the reduced frequency, $k = \omega_\alpha b / U_F$, which gives the flutter speed, also remains fixed.
- For 2D U_F is independent of scale.

Theodorsen's 2D Model



Extension to 3D FEM Model:
HAWT Blade Rotating in Still Air on a Fixed Hub

- **Use FEM (beam elements) to model structure**
- **Invoke virtual work principle to incorporate aerodynamic loads into FEM matrices (spanwise variations in chord, twist, lift coefficient, permitted)**
- **Replace airspeed, *U*, with rotational speed, Ω, which provides a linear variation in airspeed from root to tip**
- **Include rotating coordinate system terms**

$$\left[M_s + M_a(\Omega)\right]\{\ddot{u}\} + \left[C_s + C_C(\Omega) + C_a(\omega,\Omega)\right]\{\dot{u}\} + \left[K_s(u_0,\Omega) + K_{cs}(\Omega) + K_a(\omega,\Omega)\right]\{u\} = 0$$

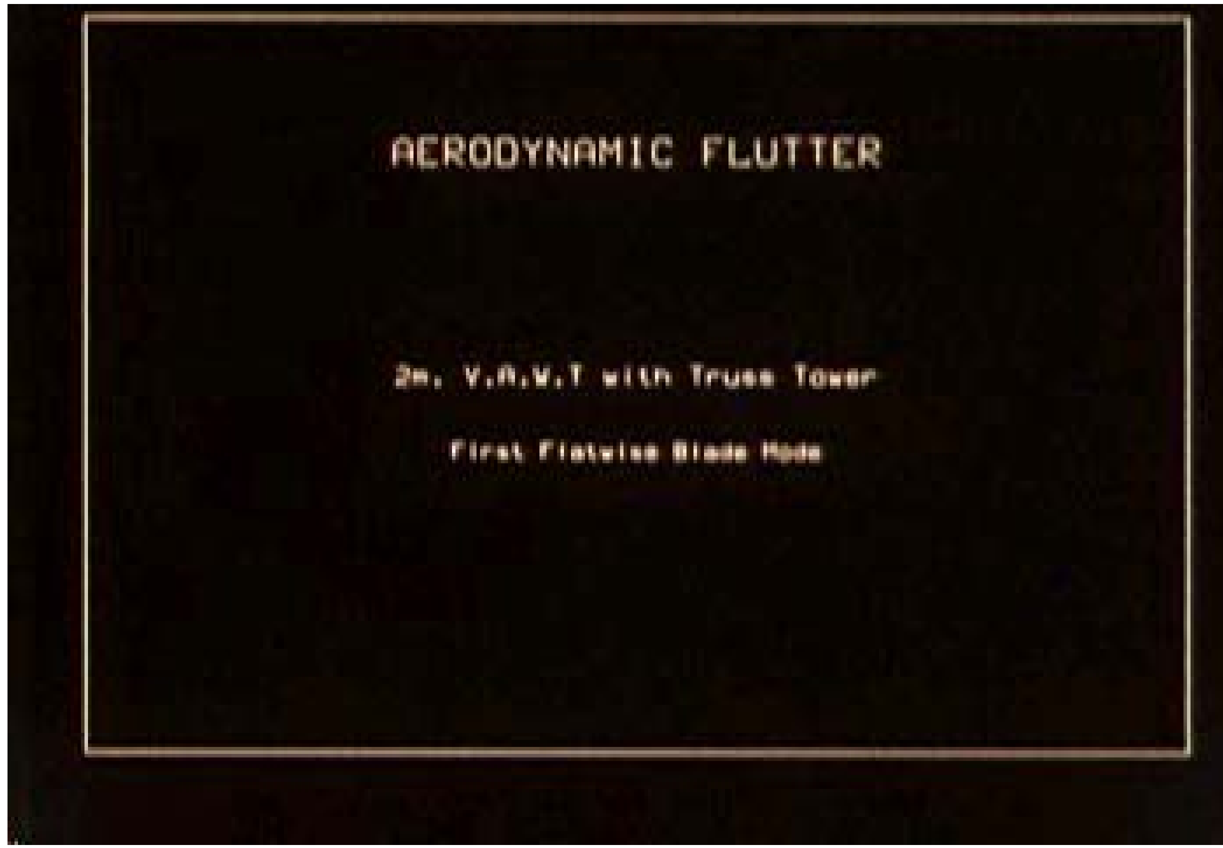
ω is the frequency of the flutter mode which is unknown a priori

Solution Details

- Frequency domain solutions required for consistency the Theodorsen Function (eigenvalue analysis)
- For a given rotational speed the frequency at which the Theodorsen function is evaluated (a priori) must coincide with the computed modal frequency of interest (iteration required)
- Rotational speed is increased until damping becomes negative (the onset of flutter)
- Generally the lowest rotational speed for flutter corresponds to the mode characterized by simple torsional motion

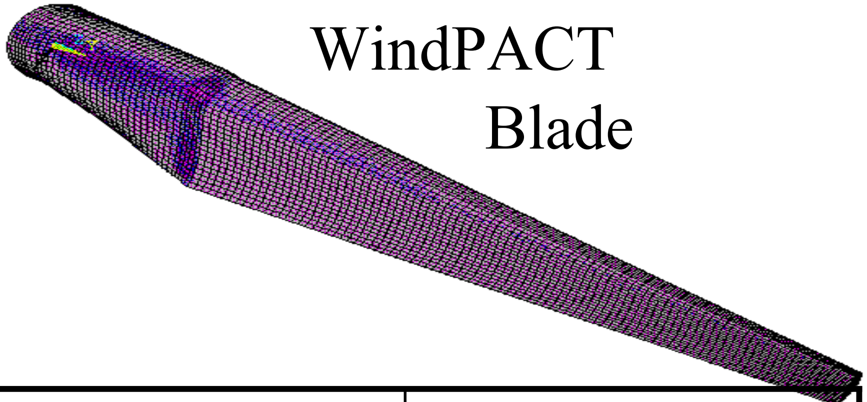
Validation Case: 3 Bladed 2m VAWT with Truss Tower

- Operating Speed: 360 rpm
- Flutter Speed (obs): 745 rpm
- Flutter Speed (pred): 680 rpm
- Flutter Mode Shape (obs): 1st flatwise mode coupled with 1st torsional mode at 90 deg phase
- Flutter Mode Shape (pred): as observed



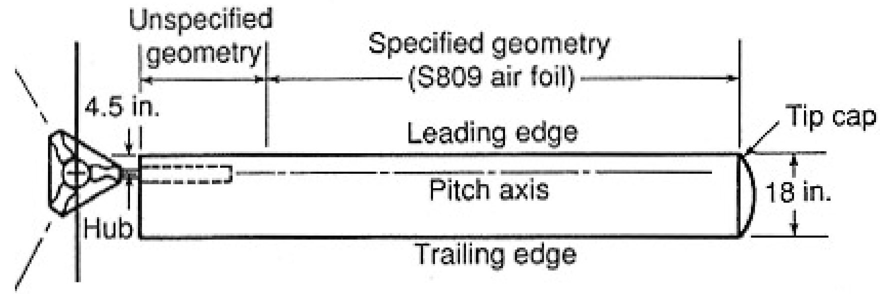
Classical Flutter Test Cases

WindPACT Blade



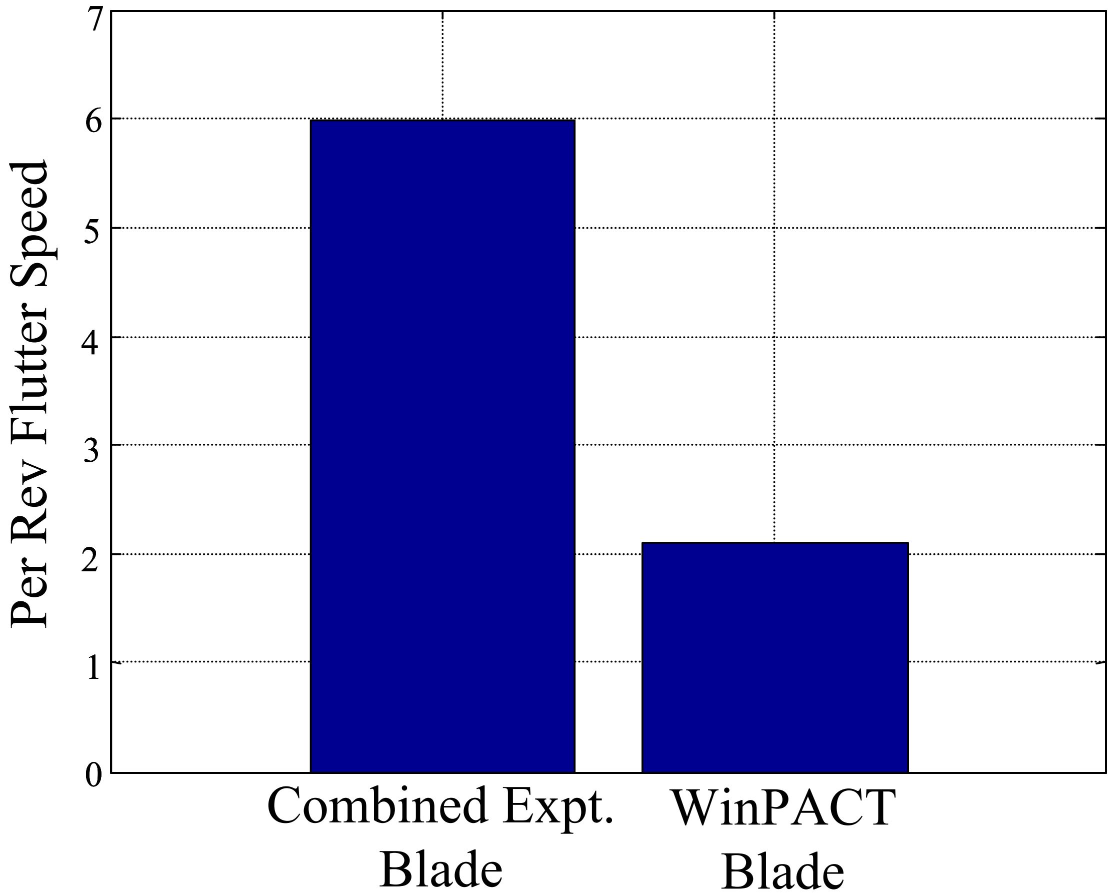
Rated power	**1.5 MW**
Rotor diameter	**70 m**
Max rotor speed	**0.342 hz (20.5 rpm)**
Max blade chord	**2.8 m**
1st flapwise freq	**1.233 hz (3.6p)**
1st edgewise freq	**1.861 hz**
2nd flapwise freq	**3.650 hz**
1st torsional freq	**9.289 hz**

Combined Experiment Blade



Rated power	**15 kW**
Rotor diameter	**10.1 m**
Rotor speed	**1.2 hz (72 rpm)**
Blade chord	**0.457 m**
1st flapwise freq	**4.8 hz (4.0p)**

Classical Flutter: 3D Results for Test Cases



Design for Preclusion of Classical Flutter

- **Attempt to move the airfoil cg ahead of the elastic axis (mass balancing)**
- **Attempt to minimize the frequency ratio ω_h/ω_α, primarily by increasing ω_α.**
- **Add damping to the structure.**
- **Decrease blade aspect ratio.**

Accuracy of Quasi-Steady Aerodynamics

Unsteady Aerodynamics

$$L = 2\pi\rho U^2 b\left\{\frac{C(k)}{U}\dot{h} + C(k)\alpha + [1 + C(k)(1-2a)]\frac{b}{2U}\dot{\alpha} + \frac{b}{2U^2}\ddot{h} - \frac{b^2 a}{2U^2}\ddot{\alpha}\right\}$$

$$M = 2\pi\rho U^2 b\left\{d_1\left[\frac{C(k)}{U}\dot{h} + C(k)\alpha + [1 + C(k)(1-2a)]\frac{b}{2U}\dot{\alpha}\right] + d_2\frac{b}{2U}\dot{\alpha} + \frac{ab^2}{2U^2}\ddot{h} - \left(\frac{1}{8} + a^2\right)\frac{b^3}{2U^2}\ddot{\alpha}\right\}$$

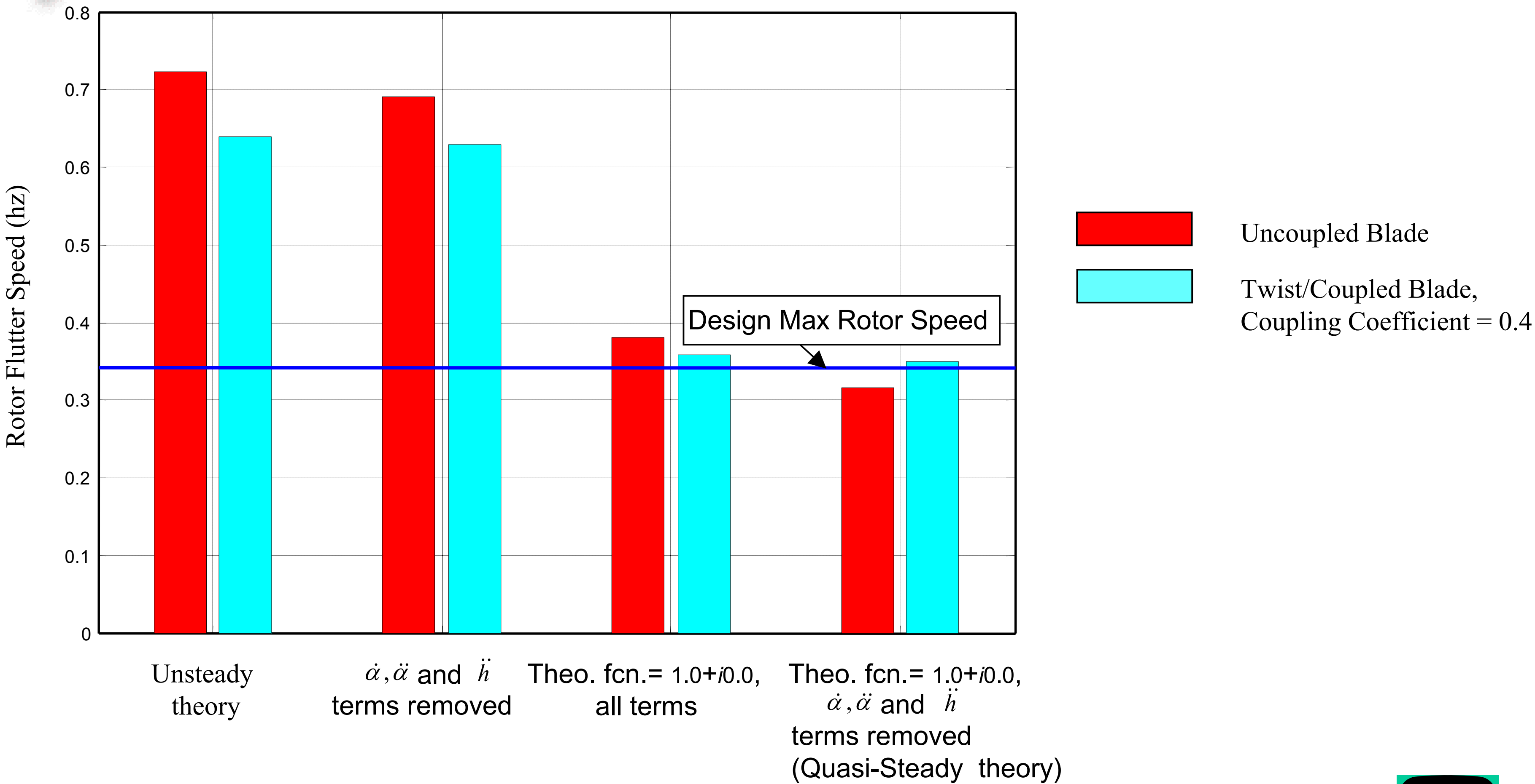
- Set the Theodorsen function, *C(k =ω b/U),* equal to unity
- Eliminate terms involving $\ddot{h}, \dot{\alpha}, \ddot{\alpha}$

$$L = 2\pi\rho U^2 b\left\{\frac{1}{U}\dot{h} + \alpha\right\}$$

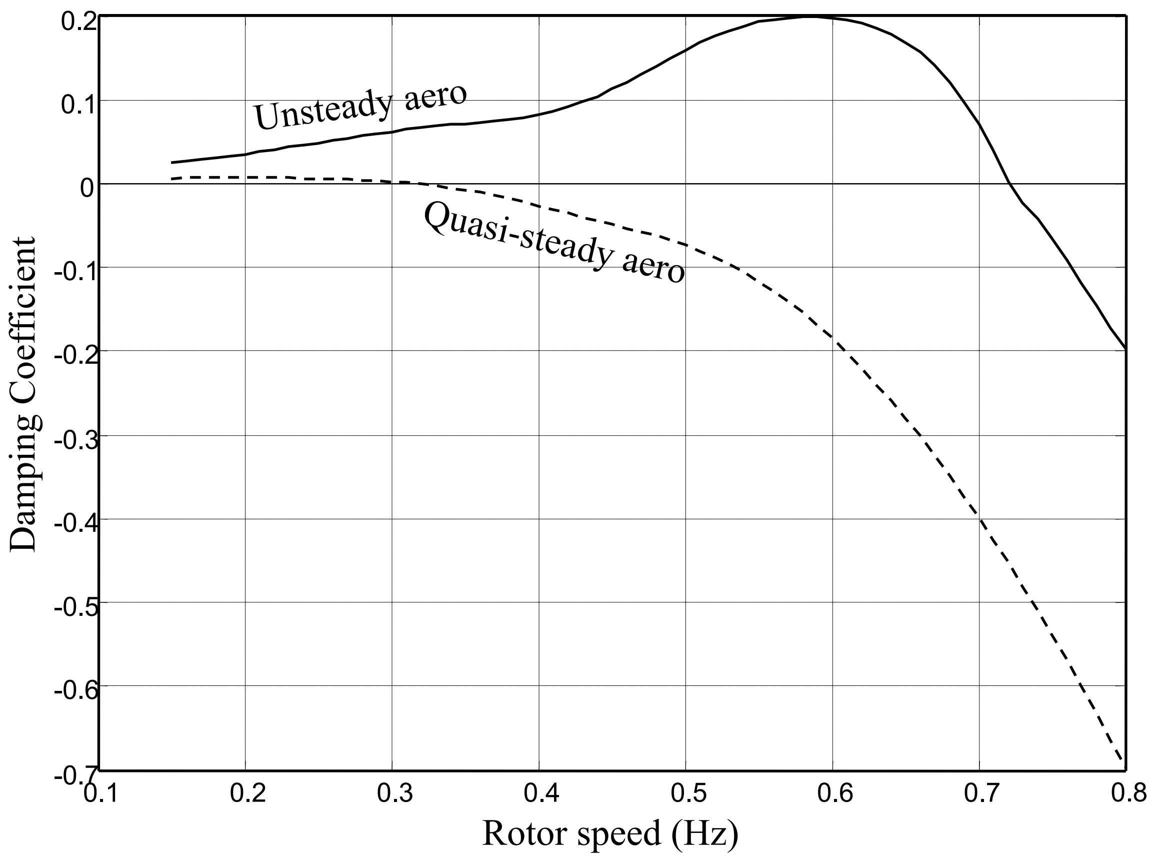
$$M = 2\pi\rho U^2 b\left\{d_1\left[\frac{1}{U}\dot{h} + \alpha\right]\right\}$$

Quasi-Steady Aerodynamics

Frequency Domain Flutter Speed Predictions Using Unsteady and Quasi-Steady Theories



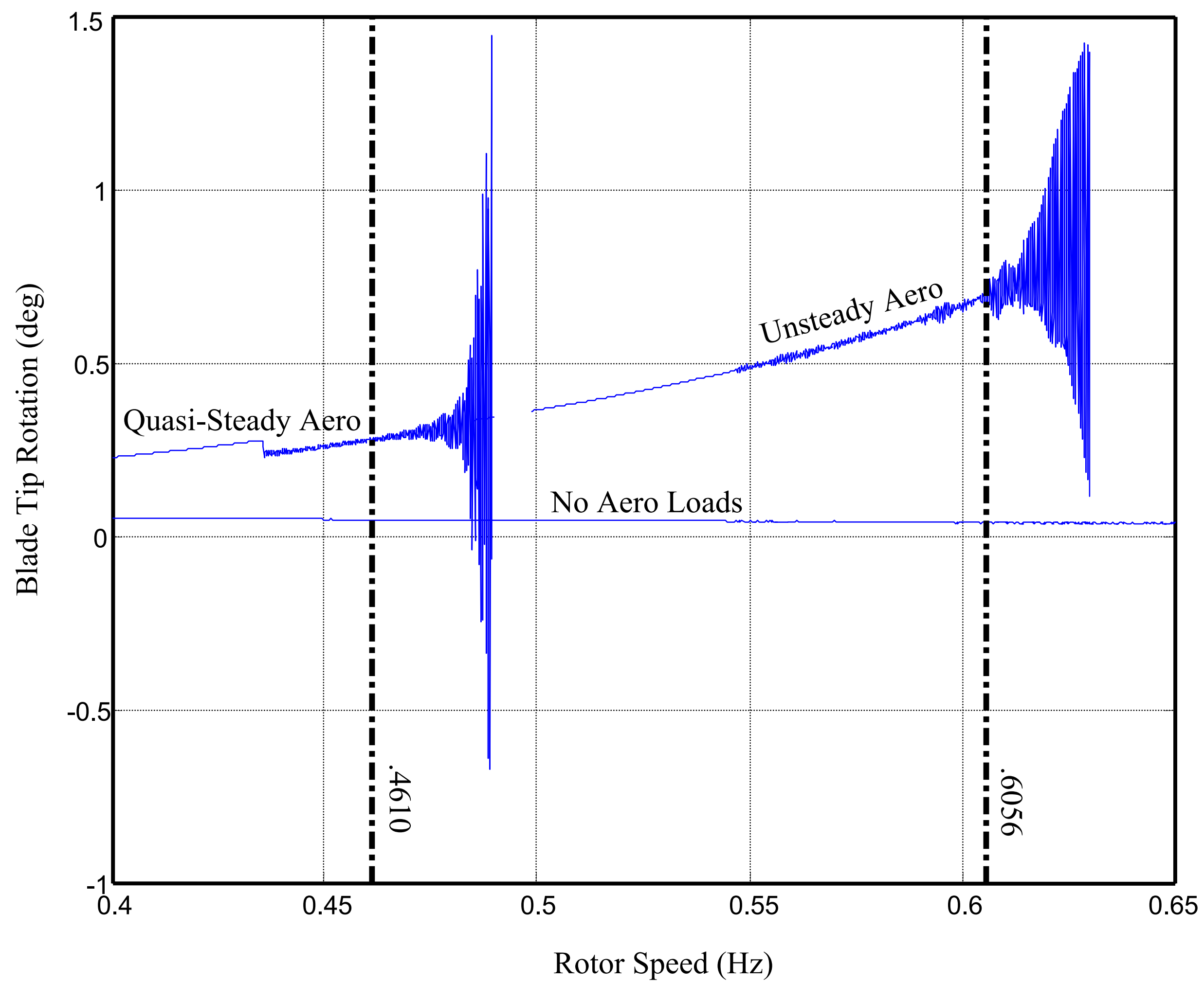
Damping Coefficient vs Rotor Speed for Flutter Mode



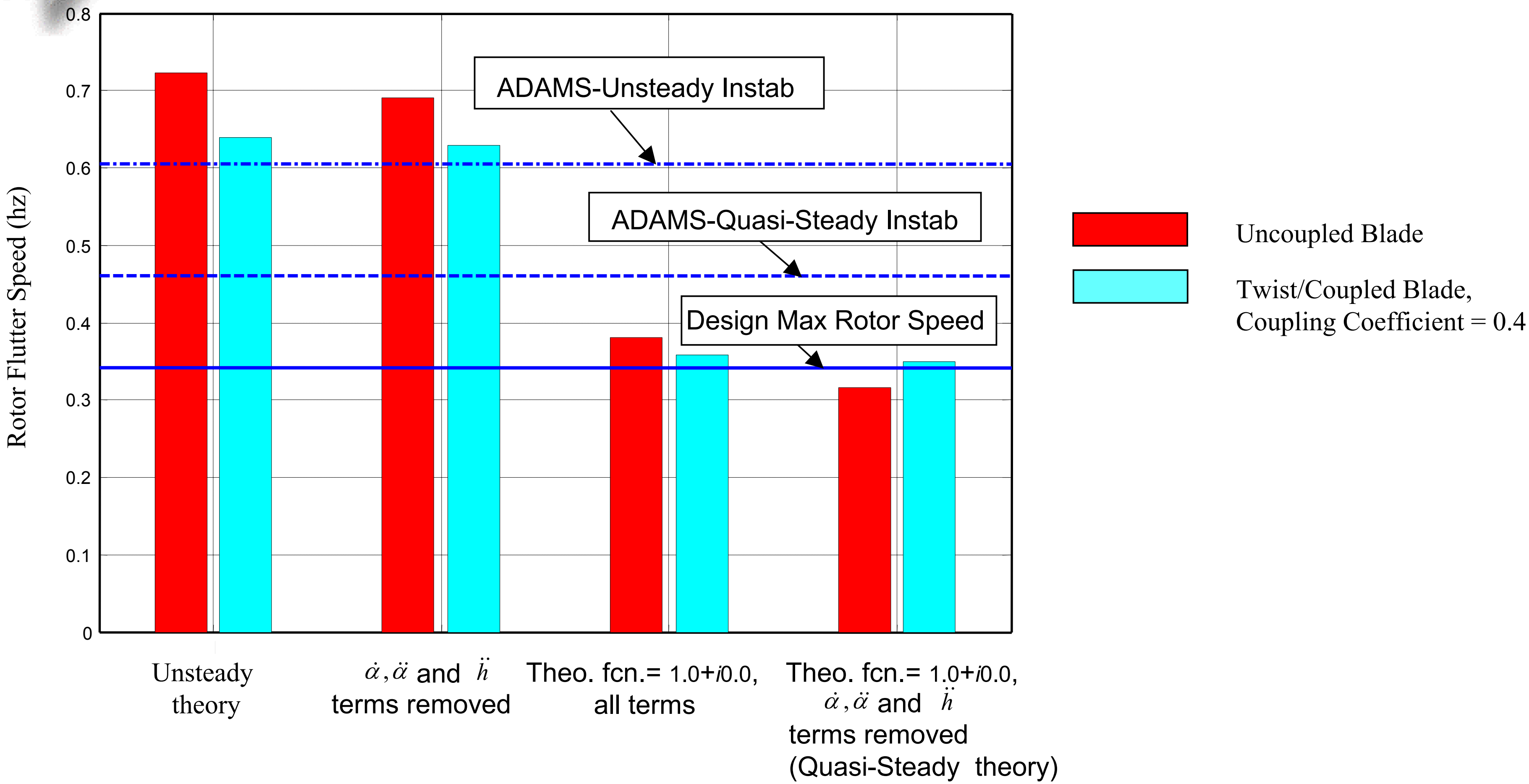
Time Domain Flutter Analysis Details

- **ADAMS/AERODYN software used**
- **Blade constrained to remain in linear aerodynamic regime through judicious selection of lift curves**
- **Aerodynamic drag and pitching moments due to the airfoil section neglected**
- **BEDDOES (Beddoes-Leishman dynamic stall model) option used to model unsteady aerodynamics (contains time domain equivalent to Theodorsen Function)**
- **STEADY option used to model quasi-steady aerodynamics**

Time Domain Flutter Speed Predictions Using the Unsteady and Quasi-Steady Theories



Comparison of Frequency Domain & Time Domain Flutter Speed Predictions



Summary and Conclusions

- **Static Panel Buckling:**
  - *** σ_{cr} is independent of scale.**
  - *** Addition of carbon while maintaining stiffness reduces σ_{cr}.**
- **Dynamic Resonance:**
  - *** Per rev natural frequencies are independent of scale.**
  - *** Softening the blade generally reduces per rev frequencies.**
  - *** Addition of carbon while maintaining stiffness generally increases per rev frequencies.**
- **Stall Flutter:**
  - *** Probably independent of scale.**
  - *** Avoided primarily by avoiding stall conditions**

Summary and Conclusions (cont.)

- **Classical Flutter:**
  * **Flutter speed for 2D and probably 3D models are independent of scale.**
  * **For a larger, modern blade design the per rev flutter speed is significantly down from that of an older, simpler and much smaller blade design (by a factor of three).**
  * **A moderate amount of twist/coupling produces a modest reduction in flutter speed (~12%).**
  * **Use of quasi-steady (vs unsteady) aerodynamics yields drastic underpredictions of the flutter speed, adversely affecting blade design by:**
    - **-- Designing to avoid fictitious premature flutter**
    - **-- Designing without the full benefit of load-mitigating aerodynamic damping**